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Multi-choice goal programming model for the optimal location of renewable energy facilities

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ABSTRACT

This paper proposes a multi-choice goal programming model for dealing with the capacity expansion planning problem of the renewable energy industry. This model involves decisions regarding the optimal mix of different plant types, location selection and other criteria. Different types of plants should be located in appropriate places so as to minimize the total deviations from predefined goals concerning power generated, investment cost, emission avoided, jobs created, operation and maintenance costs, distance security, and social acceptance. The proposed method is superior to the goal programming model proposed by Ramón and Cristóbal, in that it can avoid underestimation of aspiration level, expand the potential feasible region, and achieve findings more closely approach actual conditions. In addition, the social acceptance of the renewable energy planning problem in Taiwan is modeled by the MCGP to demonstrate its usefulness.

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1. Introduction

Because of continuous economic growth and industrialization worldwide and the soaring energy demands in the five major developing countries of Asia (China, India, Indonesia, Korea and Thailand), the demands on fossil energy for industry, transportation and daily life are becoming increasingly large. Table 1 shows the global reserves and the projected number of years of supply remaining for major fossil fuels [1,2]. Even with recent discoveries of new reserves, such as shale gas, tight sands and shale oil in North America, as well as shale oil in many other areas, fossil fuels are gradually being depleted. International oil and coal prices exceeded US $102 per barrel and US $75 per ton in April 2010 [3,4]. Since Taiwan has almost no energy resources, 97.92% of the total energy requirement depended on imports in 2013 and almost all of the fossil fuel is imported from politically unstable areas, such as the Middle East, so Taiwan's energy security has become increasingly vulnerable. Energy imports also increased from 3.88% of Taiwan's GDP in 2002 to 14.55% in 2012, which creates a large drain on Taiwan's economy. In addition, traditional uses of fossil fuels aggravate environmental pollution and the greenhouse effect. Thus, the development of renewable energy is an increasingly important issue for both developing and developed countries.

Taiwan's energy supply and consumption in 2012 are listed in Fig. 1. Compared with 2011, petroleum is 3.4% higher, renewables are 0.1% higher, nuclear is 0.2% higher, natural gas is 0.7% higher, and coal is 4% lower. This means that Taiwan is gradually improving with the use of cleaner fuels to reduce carbon emission from power generation. Since the 2011 nuclear disaster at Fukushima, the

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Table 1
Global reserves and availability of major energy resources.

Category item	Oil (+oil sanss)	Natural gas	Coal
Total reserves (end of 2011)	1481 billion barrels	196 trillion cubic meters	860 billion tons
Yield (2011)	30 billion barrels	3.2 trillion cubic meters	6.7 billion tons
Available years	49 years	61 years	112 years

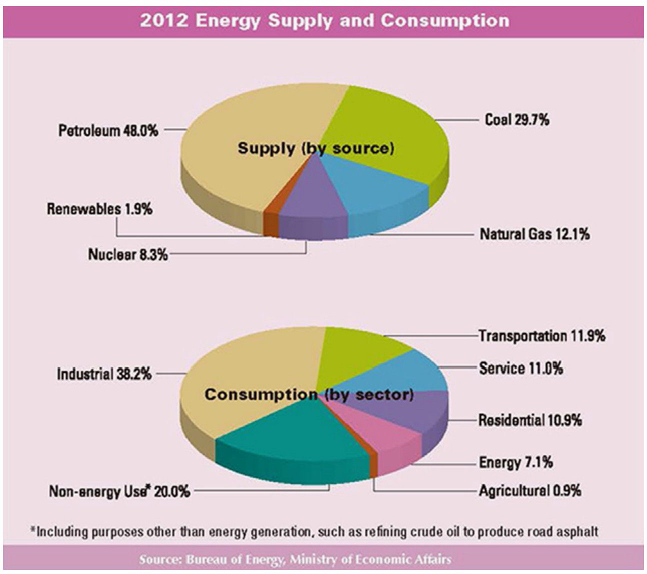


Fig. 1. 2012 Energy supply and consumption in Taiwan.

government of Taiwan has considered a nuclear energy reduction policy. Overall, it is a top priority of Taiwan to develop clean, sustainable, and independent energy and achieve a balance between energy security, environmental protection, industrial competitiveness, and economic development. This is particularly important for Taiwan's environment, with the sunny weather in southern Taiwan and abundant wind resources on the west coast of Taiwan. These issues lead to both crisis and opportunity for Taiwan in becoming a sustainable community. In order to encourage the development of renewable energy, the National Science Committee (NSC) initiated the flagship project “New Projects of Energy Technology” in 2008. Subsequently, the Ministry of Economic Affairs (MOEA) promulgated the “Renewable Energy Development Act (REDA)” in 2009, the “Incentive Program of Offshore Wind Power Demonstration System” in 2012, the “Million Solar Rooftop Photovoltaic Program” in 2013, and the “Small Wind Turbine Generation System Demonstration Incentives” in 2014. Many kinds of financial compensation are offered by the central and local governments. Further programs are also expected under the Bureau of Energy (BOE) for promoting renewable energy usage: (i) Total renewable energy capacity of 9952 MW in 2025 (i.e., 15.5% of the total power generation installation capacity in Taiwan); (ii) 1000 on- and off-shore wind turbines, with the wind power capacity of 4200 MW in 2030 and progress on the construction of the wind power system as shown in Table 2; and (iii) the “Million Solar Rooftop Photovoltaic Program” project, with photovoltaic power capacity of 3100 MW in 2030. In particular, the Industrial Technology Research Institute (ITRI), Taiwan Power Company, Chinese Petroleum Corporation, and others have begun to carry out research on renewable energy technology. From the promulgation of the REDA in 2009 to the end of 2012, the capacity of photovoltaic power increased from 11 MW to 222.4 MW, the capacity of wind power increased from 436 MW to 621 MW.

However, these infrastructure projects are often contested and face public resistance, in particular against many of the on-shore wind power projects in Taiwan. Therefore, public resistance should be considered as an important factor in a model for the optimal location of renewable energy facilities. The capacity expansion planning problem of the renewable energy industry should not only to determine the best renewable energy project among different alternatives, but also develop expansion plans for energy generation, transmission and distribution systems with consideration of the potential public resistance to these projects. This problem involves important decisions regarding the optimal solutions of different plant types, locations, and capacities. A variety of approaches have been employed to model the generation and distribution of electricity, such as of multi-criteria decision-making models [5–7], optimization models with geographic information systems for regional renewable energy development [8], and goal programming (**GP**) model for the optimal mix and location of renewable energy plants [9]. As a result, multi-criteria decision-making methods such as the Analytical Hierarchy Process (AHP), Elimination and Choice Expressing Reality (ELECTRE), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), and VIšekriterijumsko KOmpromisno Rangiranje (VIKOR) have been extensively adopted for the selection of renewable energy problems such as wind-farm projects, geothermal projects and hydro-site selection [10–16].

Though these methods have been widely applied to the renewable energy industry, the multi-choice goal programming (**MCGP**) method [17–19] has rarely been used for the location selection problem of renewable energy plants and capacity expression decisions. MCGP is a multi-choice aspiration-level approach which has been applied to many real-world problems, such as housing selection [20], low-cost carriers' networks [21], supplier selection [22,23], forestry plans [24], forestry management [25] and a piloted quality-management system [26]. Moreover, using MCGP to deal with the optimal location of renewable energy plants, can provide the following advantages:

- MCGP expands the original feasible region (it may be obtained using Weight GP, MINMAX GP, or Lexicographic GP) to the potential feasible region for obtaining the appropriate solution for decision-makers (**DMs**) responsible for the selection of the renewable energy plant location [17].
- It not only can deal with quantitative issues (e.g., minimization of operation and maintenance costs) but also qualitative problems (e.g., maximization of user satisfaction and social acceptance) [17].
- It allows DMs to set multiple aspiration levels to avoid underestimating settings determined by conservative chief-executive officers. For example, the lower power capacity of 113,609,530 W is obtained in the model of Ramón and Cristóbal (**RC**) [9] because the power generation goal (110×10^6 W) is underestimated in their model. In contrast, a higher power capacity of 116,587,600 W is obtained by the MCGP model because MCGP can reflect higher aspirations. That is, by

avoiding underestimation of the aspiration level, it is possible to have better solution in MCGP [19].

This study uses MCGP to deal with the selection of renewable energy plants, locations and the capacity expression problem by taking into account the above advantages and striving to achieve more reality-based findings. The superiority of the proposed method can be seen in the comparison of the solutions between Ramón and Cristóbal [9] and the proposed MCGP method. In addition, the MCGP is used to solve a wind power plant location selection problem in Taiwan taking into account public resistance.

2. Ramón and Cristóbal model (RC model)

In order to locate five renewable energy plants for power generation in five places located in the region of Cantabria in the north of Spain, Ramón and Cristóbal [9] proposed a novel GP model to address the problem of how to locate seven candidate plants (alternatives) in seven locations: La Braguía, La Vega, Estacas, Lunada, Potes, Reinosa and Santander. The attributes considered when evaluating these renewable energy systems in this model are: power generated (W), investment cost (I), tons of emissions of CO_2 avoided per year (TCO_2/y), jobs created (J), operation and maintenance costs (OM), distance between plants (D) and social acceptance (S). Table 3 shows the data for the first five attributes. Table 4 shows the distance between the locations. Table 5 shows the social acceptance by the local population for the hypothesized realization of the renewable energy projects. Social acceptability is expressed using a scale of 1 (low acceptance) to 10 (high acceptance). As different types of plants can be placed in each location, the goal is to ensure the minimum total deviation from the goals. These goals are given as

– (G1) The power generated must be higher than 110×10^6 W.
– (G2) The investment cost must be limited to 100×10^6€/year.

Table 2
1000 wind turbines project in Taiwan.

Years	2012	2015	2020	2025	2030
On-shore wind (MW)	621 (314 turbines)	866 (350 turbines)	1200 (450 turbines)	1200 (450 turbines)	1200 (450 turbines)
Off-shore wind (MW)	0	15 (4 turbines)	600 (120 turbines)	1800 (360 turbines)	3000 (600 turbines)
Total	621 (314 turbines)	881 (354 turbines)	1800 (570 turbines)	3000 (810 turbines)	4200 (1025 turbines)

Table 3
Alternatives for electric generation.

Alternative	W	I	TCO_2/y	J	OM
Wind power ($10 \le P \le 50$ MW)	60,959,000	23,425,000	9,649,680	15	37,750
Hydroelectric ($P \le 10$ MW)	3,940,100	7,500,000	472,812	8	7250
Hydroelectric ($10 \le P \le 25$ MW)	962,000	14,000,000	255,490	8	14,000
Hydroelectric ($25 \le P \le 50$ MW)	412,000	21,035,000	255,490	12	21,000
Solar ($P \ge 10$ MW)	306,031	5,320,000	482,856	10	1792
Biomass ($P \le 5$ MW)	13,612,500	9,015,000	2,524,643	15	27,100
Biomass ($P \ge 50$ MW)	37,770,000	47,958,400	4,839,548	20	75,000

Table 4
Distance between locations.

Alternative	La Braguía	La Vega	Estacas	Lunada	Potes	Reinosa	Santander
La Braguía	–	6.5	15	39	126	61	53
La Vega		–	8	32	121	54	65
Estacas			–	24	128	62	72
Lunada				–	143	78	56
Potes					–	130	107
Reinosa						–	75
Santander							–

Table 5
Social acceptance (1–10) of each plant in each location.

Alternative	La Braguía (8)	La Vega (9)	Estacas (10)	Lunada (11)	Potes (12)	Reinosa (13)	Santander (14)
(1) Wind power ($10 \le P \le 50$ MW)	7		9	7			9
(2) Hydroelectric ($P \le 10$ MW)	5	6			5	7	
(3) Hydroelectric ($10 \le P \le 25$ MW)	6		7	6			7
(4) Hydroelectric ($25 \le P \le 50$ MW)	4	5				6	
(5) Solar ($P \ge 10$ MW)			8	7	9		
(6) Biomass ($P \le 5$ MW)		9	8	8		9	
(7) Biomass ($P \ge 50$ MW)				9	8		9

– (G3) The emissions avoided must be higher than 18×10^6 t.
– (G4) The jobs created must be higher than 70.
– (G5) The operation and maintenance costs must be limited to 350,000€/year.
– (G6) The distance between plants must be maximized to 2910 Km.
– (G7) The social acceptance must be as close as possible to the highest level of 50.

Fig. 2 shows the multi-source multi-sink network involving seven alternatives and seven locations, a flow of k units from the source node through alternatives and place nodes to the sink node represents an assignment of k plants to places in which k compatible couples are created. This behavior can ensure that alternatives and place nodes are represented by binary variables. Then Ramón and Cristóbal [9] proposed a GP model (see [9] for details) for the optimal mix and location of renewable energy plants. In their model, the optimal mix of different plant types, locations, and capacity expansion can be easily determined using the multi-source multi-link network analysis mechanism. The compromise solutions of RC model thus obtained are shown in Table 6.

3. Improvement of application

The GP approach is a well-known and popular multi-objective mathematical programming model. It can be accomplished with various types of methods such as Lexicographic GP, Weight GP, MINMAX (Chebyshev) GP, and Extended GP [27]. Its inherent flexibility allows users to take into account several conflicting objectives, multiple criteria, and incomplete information at same time for choosing the most satisfactory solution within a feasible region. GP was first introduced by Charnes et al. (1955) and further developed by Charnes and Cooper (1961), Lee (1972), Ignizio (1985), Tamiz et al. (1998) and Romero (2001), among others [17]. In practice, the GP model minimizes $\sum_i (d_i^+ + d_i^-)$, subject to constraints $f_i(x) - d_i^+ + d_i^- = g_i$, where $x \in X \subset R^n$, d_i^+ and d_i^- are positive and negative deviations of the achievement function $f_i(x)$ from the scalar aspiration level g_i. In other words, the purpose of GP is to minimize the deviations between the achievement of goals and the scalar aspiration levels (it may be predefined by DMs for their problems).

In contrast, the role of MCGP is to aid a DM in expanding the original feasible region, which may be obtained by GP, to the potential feasible region to find more and better solutions. The MCGP model minimizes $\sum_i (d_i^+ + d_i^- + e_i^+ + e_i^-)$, subject to constraints $f_i(x) - d_i^+ + d_i^- = y_i$, $y_i - e_i^+ + e_i^- = g_{i,\max}$ or $g_{i,\min}$, where $x \in X \subset R^n$, d_i^+ and d_i^- are positive and negative deviations of the achievement function $f_i(x)$ from the vector aspiration level y_i, e_i^+ and e_i^- are positive and negative deviations of the vector achievement level y_i from the scalar aspiration level $g_{i,\max}$ or $g_{i,\min}$. Here, $g_{i,\max}(g_{i,\min})$ is the sufficiently large value for the case of the more (less) the better in real problems. In order to more closely approach reality with a potential solution than the compromise solution obtained by Ramón and Cristóbal [9], the aspiration for each goal in the model of Ramón and Cristóbal should be changed as follows:

– (G1) Power generated must be higher than 110×10^6 W and *the higher the better*.
– (G2) Investment cost must be limited to 100×10^6€/year and *the lower the better*.
– (G3) Emissions avoided must be higher than 18×10^6 t and *the higher the better*.
– (G4) Jobs created must be higher than 70 and *the higher the better*.
– (G5) Operation and maintenance costs must be limited to 350,000€/year and *the lower the better*.
– (G6) Distance between plants must be maximized to 2910 Km and *the greater the better*.
– (G7) Social acceptance must be as close as possible to the highest level of 50 and *the higher the better*.

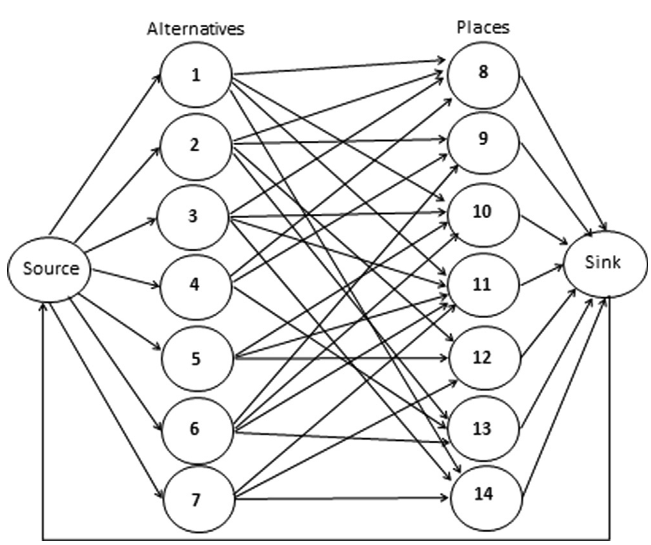


Fig. 2. Multi-source multi-sink network.

Table 7
Places to locate the plants of various models.

Alternative	MCGP–MSMS model
(1) Wind power ($10 \le P \le 50$ MW)	Estacas (10)
(2) Hydroelectric ($P \le 10$ MW)	Reinosa (13)
(5) Solar ($P \ge 10$ MW)	Potes (12)
(6) Biomass ($P \le 5$ MW)	Lunada (11)
(7) Biomass ($P \ge 50$ MW)	Santander (14)

Table 6
Solutions comparison of various models.

	W (G1)	I (G2)	TCO_2/y (G3)	J (G4)	OM (G5)	Distance (G6)	Social acceptance (G7)
Goals	110×10^6	100×10^6	18×10^6	70	350,000	2910	50
RC model	113,609,530	99,718,400	17,752,217	68	155,642	2323	43
MCGP–MSMS mdel	116,587,600	93,218,400	17,969,540	68	148,892	1043	42
MCGP–MSMS-normalized	116,587,600	93,218,400	17,969,540	68	148,892	1043	42
MCGP–MSMS-normalized[a]	113,059,500	106,753,340	17,752,220	72	162,642	1043	41
MCGP–MSMS-normalized[b]	116,587,600	93,218,400	17,969,540	68	148,892	948	43

[a] 10 times as a weight add to job created goal.
[b] 10 times as a weight add to social acceptance goal.

For treating these revised goals with new aspiration levels, this study proposes a novel method, referred to as the MCGP with a multi-source and multi-sink network (MCGP–MSMS) model for solving the capacity expansion planning problem of the renewable energy industry (see the Appendix for details). This MCGP–MSMS model is then solved using LINGO [28] to obtain the solution, as shown in Tables 6 and 7. Table 6 shows the deviations from the goals, while Table 7 and Fig. 3 show the selected locations for each plant. As seen in Table 6, goals G1, G2 and G5 are achieved, while goals G3, G4, G6 and G7 are not in both RC and MCGP–MSMS models.

It is noteworthy that the power generated (G1), investment cost (G2), emissions avoided (G3), and operation and maintenance cost (G5) achieved in MCGP–MSMS model are better than the results obtained by the model of RC [9]. Compared with the RC model, the power generated is 2.62% higher, investment cost is 6.97% lower, emissions avoided are 1.22% lower, and operation and maintenance costs are 4.53% lower in the MCGP–MSMS model. Obviously, the underestimation problem can be overcome by the proposed MCGP–MSMS model and the original feasible region in the GP has been expended to the larger potential feasible region in MCGP–MSMS [17]. The features of the MCGP–MSMS and GP are shown in Fig. 4.

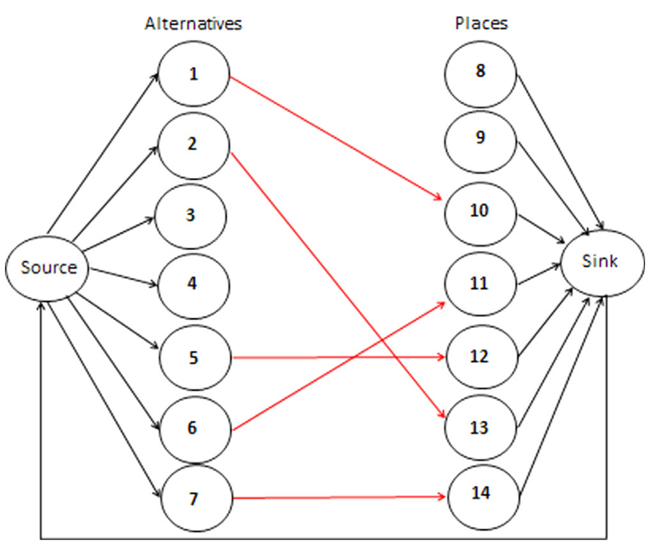


Fig. 3. The solution of MCGP–MSMS model.

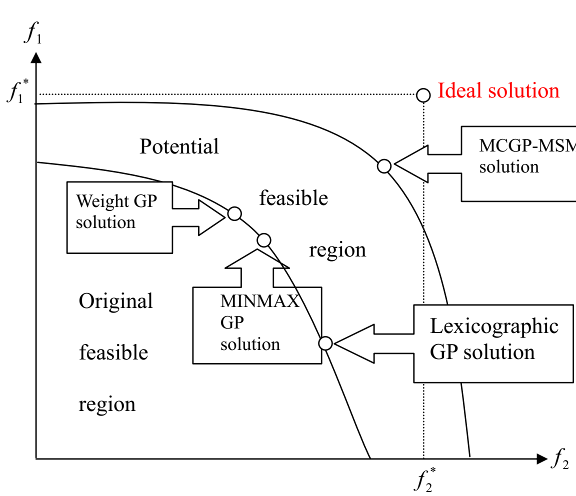


Fig. 4. Possible feasible regions in various GP methods.

Deviational variables d_i^+, d_i^-, e_i^+ and e_i^- in the model of RC [9] or MCGP–MSMS can vary in different ranges, resulting in an unintentional bias towards objectives with a large magnitude. For example, the goals of power generated and investment cost in the model of RC [9] require a relatively large value to obtain a large value in the objective function. This forces these two goals to be given higher priority than other goals to reach the target in the optimization model. Therefore, the use of a normalization technique to overcome this problem is an important issue in multiple-criteria decision-making. In order to solve this problem, the utility normalization technique (Chang [17]) is slightly modified as follows:

Let $n_k=[0,\overline{U}_k]$ and $p_k=[0,\overline{V}_k]$ $\forall k$ where $\overline{U}_k$ and $\overline{V}_k$ are the upper bounds of n_k and p_k, respectively. $D_k = Max\ \{\overline{U}_k,\ \overline{V}_k\}$ $\forall k$ and $L_j = Min\ \{\overline{U}_k,\ \overline{V}_k\}$ $\forall k$. The normalized weights are easily calculated as $w_k=(L_j/L_j+D_k)$, $w_j=(D_k/L_j+D_k)$, and $w_i=(w_j\overline{U}_k/\overline{U}_i)$ $(i\in\{1,\ldots,K\}\backslash\{j\})$. This ensures that w_k $(k=1,2,\ldots K)$ can have roughly the same magnitude as $w_k\overline{U}_k=w_i\overline{U}_i=w_j\overline{U}_j$.

For example, assume that the deviational variables d_k and n_k in the MSCP–MSMS model can vary in different ranges as $d_1, n_1=[0,120\times10^6]$, $d_2, n_2=[0,100\times10^6]$, $d_3, n_3=[0,19\times10^6]$, $d_4, n_4=[0,90]$, $d_5, n_5=[0,350000]$, $d_6, n_6=[0,4000]$, and $d_7, n_7=[0,50]$, resulting in unintentional bias toward objectives. According to the above idea, the values of $\overline{U}_k$ and $\overline{V}_k$ can be computed as follows:

$\overline{U}_1=\overline{V}_1=120\times10^6$, $\overline{U}_2=\overline{V}_2=100\times10^6$, $\overline{U}_3=\overline{V}_3=19\times10^6$, $\overline{U}_4=\overline{V}_4=90$, $\overline{U}_5=\overline{V}_5=350000$, $\overline{U}_6=\overline{V}_6=4000$, and $\overline{U}_7=\overline{V}_7=50$. $D_k=\max\{\overline{U}_k,\overline{V}_k\}=120\times10^6$, $L_j=\min\{\overline{U}_k,\overline{V}_k\}=50$, $w_1=(L_j/L_j+D_k)=0.41666\times10^{-6}$, $w_7=(D_K/L_j+D_k)=0.999999$, $w_2=(u_7\overline{U}_7/\overline{U}_2)=0.499999\times10^{-6}$, $w_3=(u_7\overline{U}_7/\overline{U}_3)=0.2631576$ $\times10^{-5}$, $w_4=(u_7\overline{U}_7/\overline{U}_4)=0.555555$, $w_5=(u_7\overline{U}_7/\overline{U}_5)=0.142857$ $\times10^{-3}$, and $w_6=(u_7\overline{U}_7/\overline{U}_6)=0.0124999$.

This ensures that d_k and n_k $(k=1,2,\ldots,7)$ can have roughly the same magnitude as $w_1\overline{U}_1=\ldots=w_7\overline{U}_7\approx50$ for deviational variables d_k and n_k in the objective function of the MSCP–MSMS model. The normalized weights applied to the MCGP–MSMS model can be expressed as follows:

(MCGP–MSMS-normalized)

Min $w_1(d_1^-+e_1^-)+w_2(d_2^++e_2^+)+w_3(d_3^-+e_3^-)+w_4(d_4^-+e_4^-)+w_5(d_5^++e_5^+)+w_6(d_6^-+e_6^-)+w_7d_7^-$

s.t. Eqs. (3.1)–(3.36).

The MCGP–MSMS-normalized model is again solved using LINGO [28] to obtain the same solution as in the MCGP–MSMS

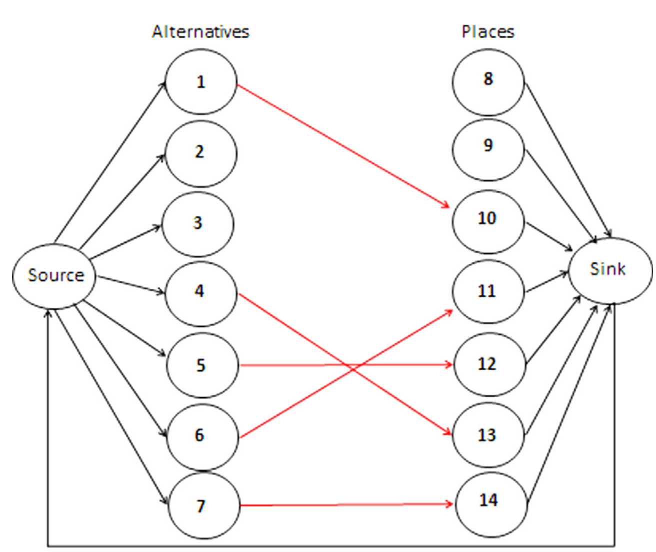


Fig. 5. The solution of MCGP–MSMS-normalized with job creation.

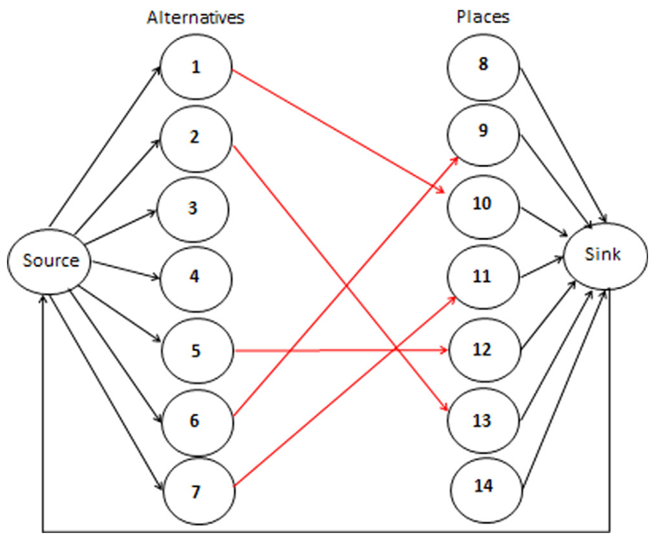


Fig. 6. The solution of MCGP–MSMS-normalized with social acceptance.

model. In order to demonstrate the usefulness of the proposed normalized mechanism, consider the following cases:

Case I: owing to the increased unemployment rate in Spain, DMs hope to increase the employment rate, so the weight added to the goal of job creation is increased by 10 times in the MCGP–MSMS-normalized model. Solving this problem with LINGO [28] yields a new solution, as shown in Table 6 and Fig. 5. As can be seen in Table 6, Goals G1, G4, and G5 are achieved, while goals G2, G3, G6 and G7 are not in both RC and MCGP–MSMS-normalized models. Notably, a value of 72 for the goal of job creation is achieved, while the highest achievements of other goals decline slightly. It is clear that using the normalized mechanism, DMs can define the appropriate weights for the MCGP–MSMS-normalized model to achieve their particular goals.

Case II: due to public resistance, DMs would like to increase the social acceptance rate to the maximum possible value, and to do so the weight added to the goal of social acceptance is increased by 10 times in the MCGP–MSMS-normalized model. This problem is solved with LINGO [28] to obtain the solution shown in Table 6 and Fig. 6. Fig. 6 shows the locations for each plant. As seen in Table 6, Goals G1, G2, and G5 are achieved, while goals G3, G4, G6 and G7 are not in both RC and MCGP–MSMS-normalized models. Notably, a value of 43 for the goal of social acceptance rate is achieved, which is the highest social acceptance rate in this case, while the highest achievements of other goals are slightly lower. Compared with the RC model, the power generated is 2.62% higher, investment cost is 6.97% lower, emissions avoided are 1.22% higher, and operation and maintenance costs are 4.53% lower in the MCGP–MSMS-normalized model. It is seen that by adding weights to the objective function, the proposed method can easily be used as a decision aid to determine the best or most appropriate solution to multiple objective problems. Each goal of the multiple objective problem can be divided to multiple aspiration levels to better suit management requirements, such as "the more the better " or "the less the better". These constraints can also be easily added in the MCGP–MSMS-normalized model to mirror real-world situations. The MCGP–MSMS-normalized model provides a feasible and robust way to choose an optimal location for renewable energy plants.

4. Social acceptance of a wind turbine installation

Due to the abundant wind resources on the west coast of Taiwan, 28 possible on-shore locations are evaluated for implementation of wind turbine generation systems, as shown in Fig. 7. Though there were 314 wind turbine systems installed in 2012, generating 621 MW, due to the greater awareness of environmental protection issues and participatory democracy, protests against proposed wind turbine installation have occurred, such as the public resistance from Yuan Li township, Penghu county, XinWu township, Tongxiao township, Sanzhi district, Zhunan township, and others. As shown in Table 2, there are 886 wind turbines scheduled to be installed by 2030, though due to popular protests this will be the most difficult part of the subsequent installation of wind turbines in Taiwan. In the past decade, there have been many studies on quantitative goals (e.g., maximize power generated) in determining the optimal location of renewable energy facilities. However, qualitative goals, such as individual preferences (e.g., minimize popular protests) have rarely been addressed in solutions to this problem. The second objective of this study is to provide a feasible method for dealing with the qualitative problem of reducing public resistance, in order to facilitate subsequent installation of wind power system. For simplicity, the linear utility function is given as the following two membership functions (**MF**), $\eta_i(f_i(x))$, to represent social acceptance rate for the wind turbines installation. A graph representation of MF is shown in Fig. 8. (4.1) is used to maximize $f_i(x) \gtrsim g_i$ in order to increase the social acceptance rate (e.g., the greater the financial compensation, the higher the social acceptance rate).

$$\eta_i(f_i(x)) = \begin{cases} 1, & \text{if} \quad f_i(x) \geq g_i \\ \frac{f_i(x) - l_i}{g_i - l_i}, & \text{if} \quad l_i < f_i(x) < g_i \\ 0, & \text{if} \quad f_i(x) \leq l_i \end{cases}, \text{ (the right linear MF)} \tag{4.1}$$

(4.2) is used to minimize $f_i(x) \lesssim g_k$ in order to increase the social acceptance rate (e.g., the less the wind turbine noise, the higher the social acceptance rate).

$$\eta_i(f_i(x)) = \begin{cases} 1, & \text{if} \quad f_i(x) \leq g_i \\ \frac{u_i - f_i(x)}{u_i - g_i}, & \text{if} \quad g_i < f_i(x) < u_i \\ 0, & \text{if} \quad f_i(x) \geq u_i \end{cases}, \text{ (the left linear MF)} \tag{4.2}$$

where u_i and l_i are the respective upper and lower tolerance limits for the ith goal. The achievement model with the MFs, can be formulated as follows:

(MCGP-U)

$$\text{Min} \sum_{i=1}^{n} [\alpha_i(d_i^+ + d_i^-) + \beta_i(e_i^+ + e_i^-) + \lambda f_i^- + \psi h_i^-]$$

$$\left.\begin{array}{l} \text{s.t. } \eta_i(f_i(x)) = \frac{f_i(x) - l_i}{g_i - l_i}, \text{ the right linear MF} \\ f_i(x) - d_i^+ + d_i^- = g_i, \text{ the upper limit value } g_i \\ \eta_i(f_i(x)) + f_i^- = 1, \text{ the highest value of 1} \end{array}\right\} \text{for } f_i(x) \gtrsim g_i$$

$$\left.\begin{array}{l} \eta_i(f_i(x)) = \frac{u_i - f_i(x)}{u_i - g_i}, \text{ for left linear MF} \\ f_i(x) - e_i^+ + e_i^- = g_i, \text{ the lower limit value } g_i \\ \eta_i(f_i(x)) + h_i^- = 1, \text{ the highest value of 1} \end{array}\right\} \text{for } f_i(x) \lesssim g_k$$

$$d_i^+,\ d_i^-,\ f_i^-,\ \mu_i(f_i(x)) \geq 0$$

$x \in F$ (F is a feasible set)

where $\alpha_i, \beta_i, \lambda_i$, and ψ_i are the weights attached to the deviational variables, $d_i^+, d_i^-, e_i^+, e_i^- f_i^-$, and h_i^-.

In general, Taiwan citizens are opposed to high-polluting coal-fired and fossil fuel power generation, and the safety of nuclear power is also an issue of public concern, so there is support for renewable energy. But residents still do not want to have wind turbines sited too closed to their dwellings, schools or workplaces since wind turbines are a source of noise in rural environments. The most common complaints and source of social resistance to wind farms are noise and blade flicker (glare reflecting off the

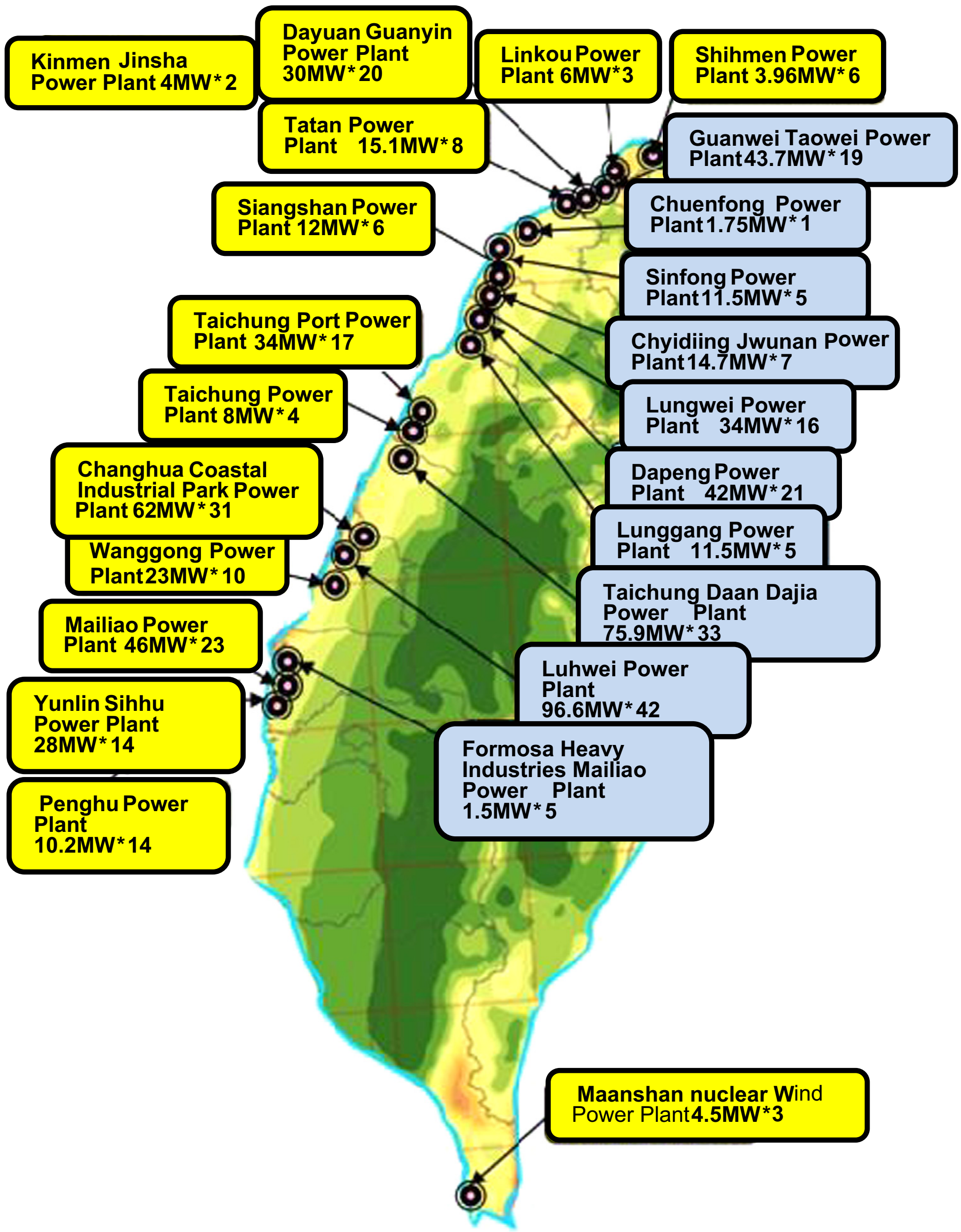


Fig. 7. On-shore win farms in Taiwan (Source:ITRI).

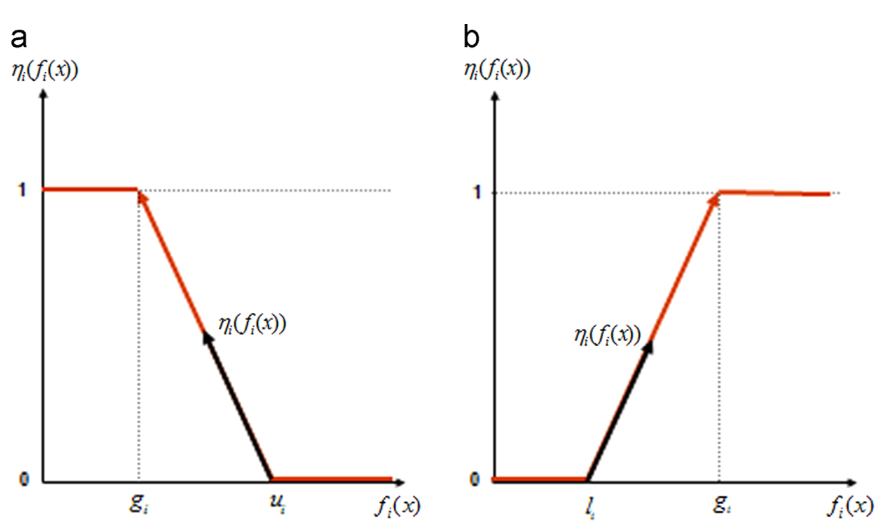


Fig. 8. The linear utility function (a) Left linear membership function and (b) right linear membership function.

spinning turbine blades). Especially, the lower frequencies of noise from the wind turbine are judged to be very annoying during the night. These two issues are directly related to the distance from the wind turbines to residents homes. Thus people would like to maximize the distance between wind turbine installations and their dwelling and workplaces, to achieve higher satisfaction.

But due to the costs associated with construction and land acquisition, and considering Taiwan's dense population, it is often difficult to fully meet the requirements of residents. So, finding a balance between the requirements of residents and construction considerations is the most important issue. For sake of simplicity, three basic attributes are taken into consideration: power generated (MW), investment cost (I), and social acceptance (S) with MF. Table 8 shows the data for MW and I attributes. Table 9 shows five candidate locations for the installation of wind turbines. Table 10 shows the social acceptance with MF. Based on (4.1) and Table 10, all possible levels of social acceptance (satisfaction) for wind turbine locations are calculated, as shown in Table 11. Four possible wind turbines installations (see Table 8) for power generation in five possible locations (see Table 9) must be evaluated in order to satisfy the following goals.

- (G1) Power generated must be higher than 15 MW and *the higher the better*.
- (G2) Investment cost must be limited to 50 × 10^6\$/year and *the lower the better*.
- (G3) Social acceptance must be limited to the level of 50 and *the higher the better*.

Table 8
Alternatives for electric generation.

Alternative	Variables	MW	I (US$)
Wind turbine 1 ($1 \le P \le 2$ MW)	x_1	1.98	3,280,000
Wind turbine 2 ($2 \le P \le 4$ MW)	x_2	3.92	6,560,000
Wind turbine 3 ($4 \le P \le 10$ MW)	x_3	9.12	9,840,000
Wind turbine 4 ($10 \le P \le 15$ MW)	x_4	14.55	10,500,000

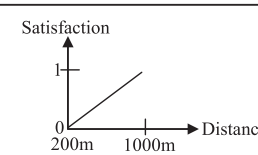
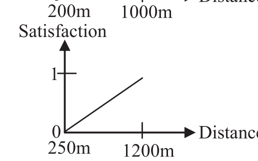
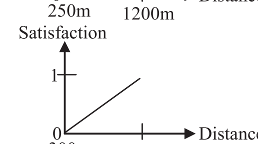
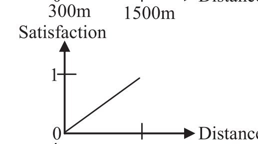
Table 9
Five places attributes.

Places	Distance to residents house (m)	Land cost (US$)
5	300	70,000
6	500	90,000
7	600	98,000
8	1200	140,000
9	450	80,000

Table 11
Satisfaction of wind turbine installation.

Alternative	Place	Value of MF (satisfaction)
Wind turbine 1	5	0.125
	6	0.375
	7	0.5
	8	1
	9	0.3125
Wind turbine 2	5	0.052
	6	0.263
	7	0.368
	8	1
	9	0.21
Wind turbine 3	5	0
	6	0.166
	7	0.25
	8	0.75
	9	0.125
Wind turbine 4	5	0
	6	0.09
	7	0.18
	8	0.727
	9	0.045

Table 10
Wind turbine (noise vs. social acceptance).

Alternative	Distance noise	Social acceptance	Corresponding MF	Graphs
Wind turbine 1 ($1 \le P \le 2$ MW)	[200 m,1000 m]=[40 db,30 db]	[0,1]	(4.1) right linear MF	
Wind turbine 2 ($2 \le P \le 4$ MW)	[250 m,1200 m] =[42 db,35 db]	[0,1]	(4.1) right linear MF	
Wind turbine 3 ($4 \le P \le 10$ MW)	[300 m,1500 m] =[45 db,38 db]	[0,1]	(4.1) right linear MF	
Wind turbine 4 ($10 \le P \le 15$ MW)	[400 m,1500 m] =[46 db,39 db]	[0,1]	(4.1) right linear MF	

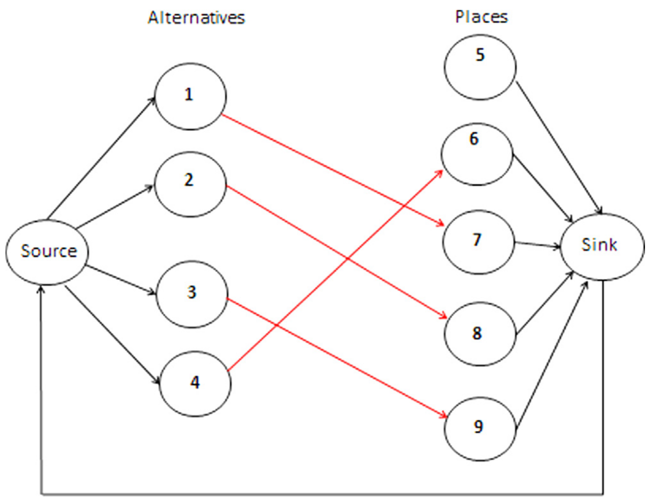


Fig. 9. The solution of MCGP-U without weight.

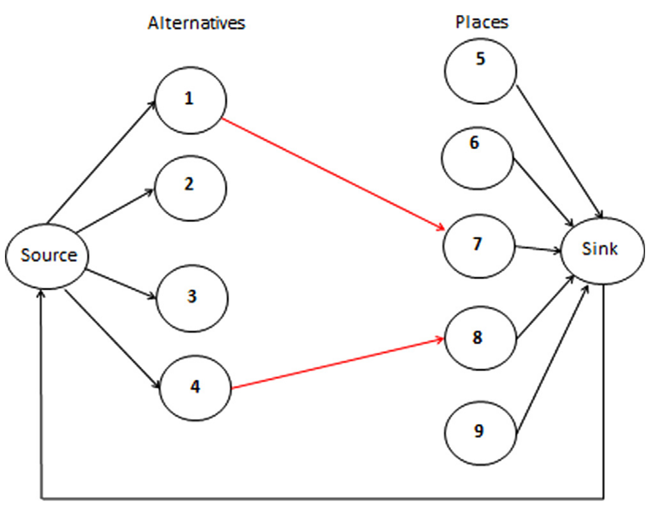


Fig. 10. The solution of MCGP-U with weight.

The achievement model without adding weights to each goal is formulated using the proposed model MCGP-U (see the Appendix for details). The model is then solved using LINGO [28] to obtain the solution as (MW, I, S)=(29.57, 34.26 × 10^6, 0.4287). Fig. 9 shows the locations for each wind turbine installation. As the result the following goals are achieved: social acceptance of 42.87%, power generation of 197%, investment cost of 131.5% achieved. Clearly, the problem can easily be solved using the proposed MCGP-U. In order to increase the social acceptance rate, a large weight is added to G3. Then, the problem is solved again to obtain solution as (MW, I, S)=(16.53, 16.16 × 10^6, 0.6135). Fig. 10 shows the places where each wind turbine should be located for higher social acceptability. As seen in this solution, the social acceptance rate increases from 42.87% to 61.35% when the large weight is increased to G3. This shows that the proposed model provides feasible features for a DM to deal with multiple decision making problems.

5. Conclusions

Mitigation of climate change and environmental pollution has increased the need to replace fossil fuel energy with renewable energy world-wide. The capacity expansion planning problem of renewable energy industry is an important issue for both developing and developed counties in the implementation of appropriate renewable energy policies. To deal with this problem, Ramón and Cristóbal [9] proposed a method in which an optimal outcome of plant types, numbers of plants and locations can be easily determined. In this study, a MCGP model is proposed to improve the usefulness of that model of through an example of locating five renewable energy plants for power generation in five locations in the autonomous region of Cantabria, in the north of Spain. Moreover, the normalization method is introduced to the MCGP for helping DMs to set appropriate weights according to their preferences or policies. As a result, MCGP can be used as an efficient, effective and feasible tool for DMs when dealing with the capacity expansion planning problem of renewable energy industry. In addition, social acceptance of a wind turbine installation in Taiwan is also considered.

Appendix

(MCGP–MSMS)

Min $d_1^- + e_1^- + d_2^+ \ + e_2^+ + d_3^- + e_3^- + \ d_4^- + e_4^- + d_5^+ + e_5^+ + \ d_6^- + e_6^- + d_7^-$

s.t.—The following for power generated goal (the case of the more the better):

$$60,959,000F_{1,8} + \ldots + 37,770,000 \ F_{7,14} - d_1^+ + d_1^- = y_1, \tag{3.1}$$

$$y_1 - e_1^+ + e_1^- = 120 \times 10^6, \tag{3.2}$$

$$110 \times 10^6 \le y_1 \le 120 \times 10^6, \text{the sufficiently large value for power generated is } 120 \times 10^6 \text{ W} \tag{3.3}$$

The following for investment (the case of the less the better):

$$23,425,000F_{1,8} + \ldots + 47,958,000F_{7,14} - d_2^+ + d_2^- = y_2, \tag{3.4}$$

$$y_2 - e_2^+ + e_2^- = 80 \times 10^6, \tag{3.5}$$

$$80 \times 10^6 \le y_2 \le 100 \times 10^6, \text{the sufficiently small value for investment is } 80 \times 10^6 \tag{3.6}$$

The following for emission avoided goal (the case of the more the better):

$$9,649,680F_{1,8} + \ldots + 4,839,548F_{7,14} - d_3^+ + d_3^- = y_3, \tag{3.7}$$

$$y_3 - e_3^+ + e_3^- = 19 \times 10^6, \tag{3.8}$$

$$18 \times 10^6 \le y_3 \le 19 \times 10^6, \text{the sufficiently large value for emission avoided is } 19 \times 10 \text{ t} \tag{3.9}$$

The following for jobs created goal (the case of the more the better):

$$15F_{1,8} + \ldots + 20F_{7,14} - d_4^+ + d_4^- = y_4, \tag{3.10}$$

$$y_4 - e_4^+ + e_4^- = 90, \tag{3.11}$$

$$70 \le y_4 \le 90, \text{the sufficiently large value for jobs created is } 90 \tag{3.12}$$

The following for operation and maintenance costs goal (the case of the less the better):

$$37750F_{1,8} + \ldots + 75,000F_{7,14} - d_5^+ + d_5^- = y_5, \tag{3.13}$$

$$y_5 - e_5^+ + e_5^- = 300000, \tag{3.14}$$

$300000 \le y_5 \le 350000$, the sufficiently small value for OM costs is 300000 (3.15)

The following for total distance between nodes goal (the case of the more the better):

$$6.5F_{8sii}F_{9si} + \ldots + 75F_{13si}F_{14si} - d_6^+ + d_6^- = y_6, \tag{3.16}$$

$$y_6 - e_6^+ + e_6^- = 4000, \tag{3.17}$$

$2910 \le y_6 \le 4000$, the sufficiently large value for total distance is 4000 (3.18)

The following for social acceptance goal (the case of the more the better):

$$7F_{1,8} + \ldots + 9F_{7,14} - d_7^+ + d_7^- = 50, \tag{3.19}$$

$$F_{sosi} - F_{so1} - F_{so2} - F_{so3} - F_{so4} - F_{so5} - F_{so6} - F_{so7} = 0, \tag{3.20}$$

$$F_{8si} + F_{9si} + F_{10si} + F_{11si} + F_{12si} + F_{13si} + F_{14si} - F_{siso} = 0, \tag{3.21}$$

$$F_{18} + F_{28} + F_{38} + F_{48} - F_{8si} = 0, \tag{3.22}$$

$$F_{29} + F_{49} + F_{69} - F_{9si} = 0, \tag{3.23}$$

$$F_{110} + F_{310} + F_{510} + F_{610} - F_{10si} = 0, \tag{3.24}$$

$$F_{111} + F_{311} + F_{511} + F_{611} + F_{711} - F_{11si} = 0, \tag{3.25}$$

$$F_{212} + F_{512} + F_{712} - F_{12si} = 0, \tag{3.26}$$

$$F_{213} + F_{413} + F_{613} - F_{13si} = 0, \tag{3.27}$$

$$F_{114} + F_{314} + F_{714} - F_{14si} = 0, \tag{3.28}$$

$$F_{so1} - F_{18} - F_{110} - F_{114} = 0, \tag{3.29}$$

$$F_{so2} - F_{28} - F_{29} - F_{212} - F_{213} = 0, \tag{3.30}$$

$$F_{so3} - F_{38} - F_{310} - F_{311} - F_{314} = 0, \tag{3.31}$$

$$F_{so4} - F_{48} - F_{49} - F_{413} = 0, \tag{3.32}$$

$$F_{so5} - F_{510} - F_{511} - F_{512} = 0, \tag{3.33}$$

$$F_{so6} - F_{69} - F_{610} - F_{611} - F_{613} = 0, \tag{3.34}$$

$$F_{so7} - F_{711} - F_{712} - F_{714} = 0, \tag{3.35}$$

$$F_{8si} + F_{9si} + F_{10si} + F_{11si} + F_{12si} + F_{13si} + F_{14si} = 5, \tag{3.36}$$

where Eqs. (3.1)–(3.19) correspond to the goals power, investment, emissions, jobs, operation and maintenance, and social acceptance; and Eqs. (3.20)–(3.36) are the conservation of flow constraints for each node.

(MCGP-U)

$$\text{Min } d_1^- + d_1^+ + e_1^- + e_1^+ + d_2^- + d_2^+ + e_2^- + e_2^+$$

s.t. —The following for power generated goal (the case of the more the better):

$$1.98F_{15} + 1.98F_{16} + \ldots + 14.55F_{49} - d_1^+ + d_1^- = y_1 \tag{4.1}$$

$$10 \le y_1 \le 30, \tag{4.2}$$

$$y_1 - e_1^+ + e_1^- = 30, \tag{4.3}$$

The sufficiently large value for power generated is 30 MW (4.4)

The following for investment (the case of the less the better):

$$(3,280,000 + 700,000)F_{15} + \ldots + (10,500,000 + 800,000)F_{49} - d_2^+ + d_2^- = y_2, \tag{4.5}$$

$$5,000,000 \le y_2 \le 10,000,000, \tag{4.6}$$

$$y_2 - e_2^+ + e_2^- = 5,000,000, \tag{4.7}$$

The following for social acceptance (the case of the more the better):

$$\frac{0.125F_{15} + 0.375F_{16} + \ldots + 0.045F_{49}}{F_{15} + F_{16} + \ldots + F_{49}} - d_3^+ + d_3^- = y_3, \tag{4.8}$$

$$0.5 \le y_3 \le 1, \tag{4.9}$$

$$y_3 - e_3^+ + e_3^- = 1, \tag{4.10}$$

The following for one wind turbine can only assign one place, and vice versa:

$$\sum_{j=5}^{9} F_{ij} \le 1, \quad i = 1,2,3,4 \tag{4.11}$$

$$\sum_{i=1}^{4} F_{ij} \le 1, \quad j = 1,2,3,4,5. \tag{4.12}$$

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